Cyber-Physical Materials

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Overview

Computational Meta-Materials (CMMs) are cyber-physical systems that gain their properties from their structure and embedded sensing, actuation, computation, and control (SAC^2). CMMs are a new class of bio-inspired materials that allow unprecedented multi-functionality through their ability to be programmed. This feature enables arbitrary spatio-temporal behaviors that could be used in such applications as camouflage and morphable or reconfigurable surfaces and structures.

Figure: CMMs are inspired from biological systems such as Cuttlefish that rapidly change the color of their skin for camouflage, manta rays that move through the water by flexing their fins, and sea cucumbers that essentially liquefy themselves to maneuver through small openings.

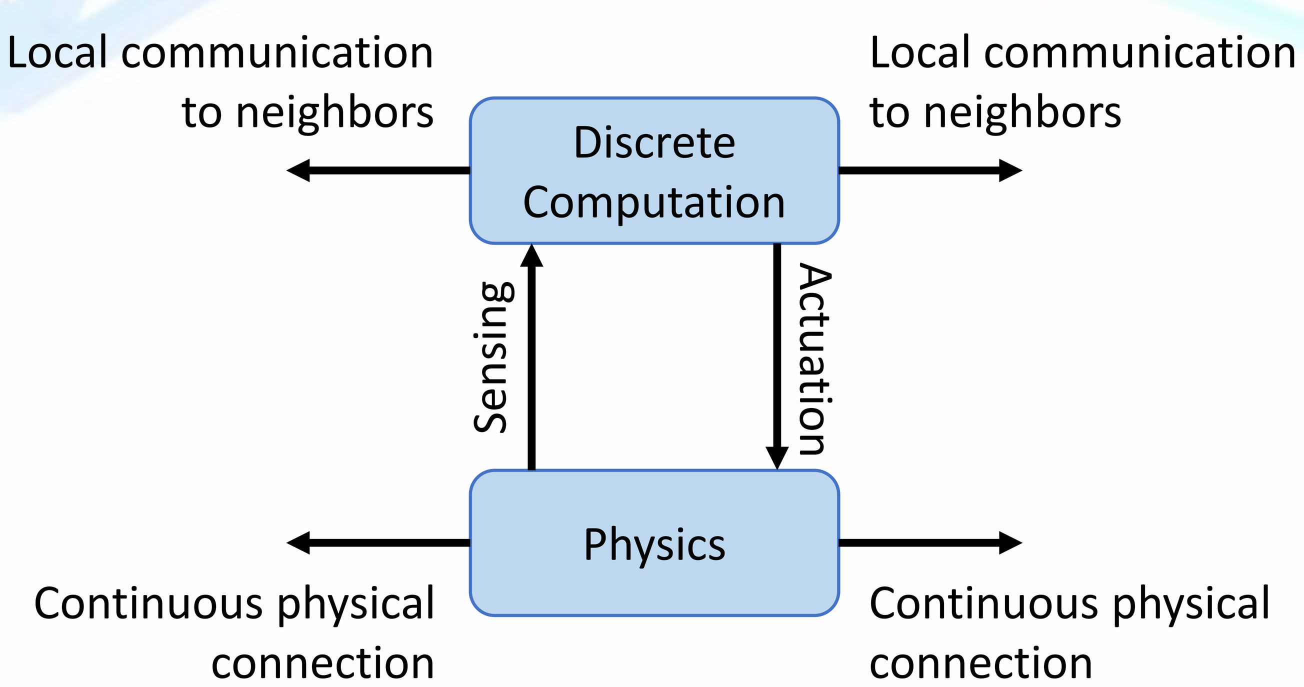

Figure: The diagram above shows the cyber-physical model of CMMs. In this vision, SAC^2 will be distributed throughout a material and will locally control key material attributes so that the materials can become an interactive part of our environment.

Example: Shape Change

The shape of the beam is related to the applied moments and the stiffness of the beam (physical aspect).

$$v''(x,t)E(x,t)I = M(x,t)\left(1 + v'(x,t)^2\right)^{1.5}$$

Using a thermoplastic, the stiffness of a beam can be controlled by a change in temperature so that $E(x,t) = f\big(T(x,t)\big)$ (cyber aspect).

$$\dot{E} = -p\big(\hat{E} - E_{set}\big) \Rightarrow \dot{E} \approx -p\big(\hat{T} - T_{set}\big)$$

Where E is the young's modulus, I is the cross-sectional inertia, M is the applied moment, v is the vertical displacement, and T is the temperature of the bar.

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Example: Shape Change (continued)

Below is a cross-section of a morphable CMM showing the embedded components. A change in shape is brought about by the coupled stiffness and applied force functions, both of which vary with time and along the length of the bar. Also shown is the bar changing shape under a set of chosen stiffness and force profiles.

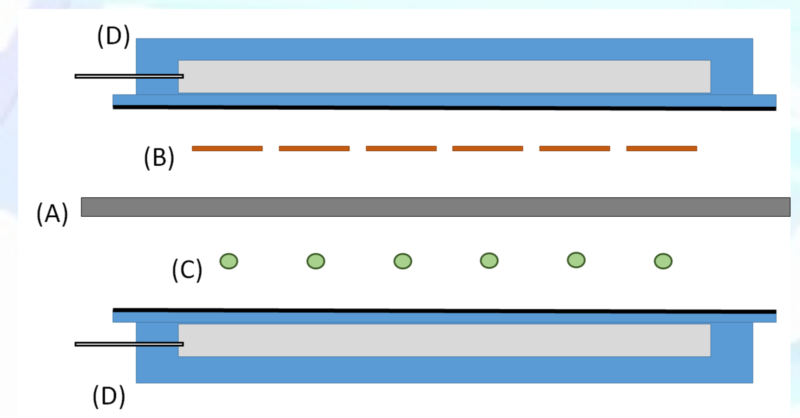

Figure: A thermoplastic bar (A) is embedded with heaters (B) and thermistors (C). Simple 1D pneumatic actuators (D) apply a distributed force along the bar.

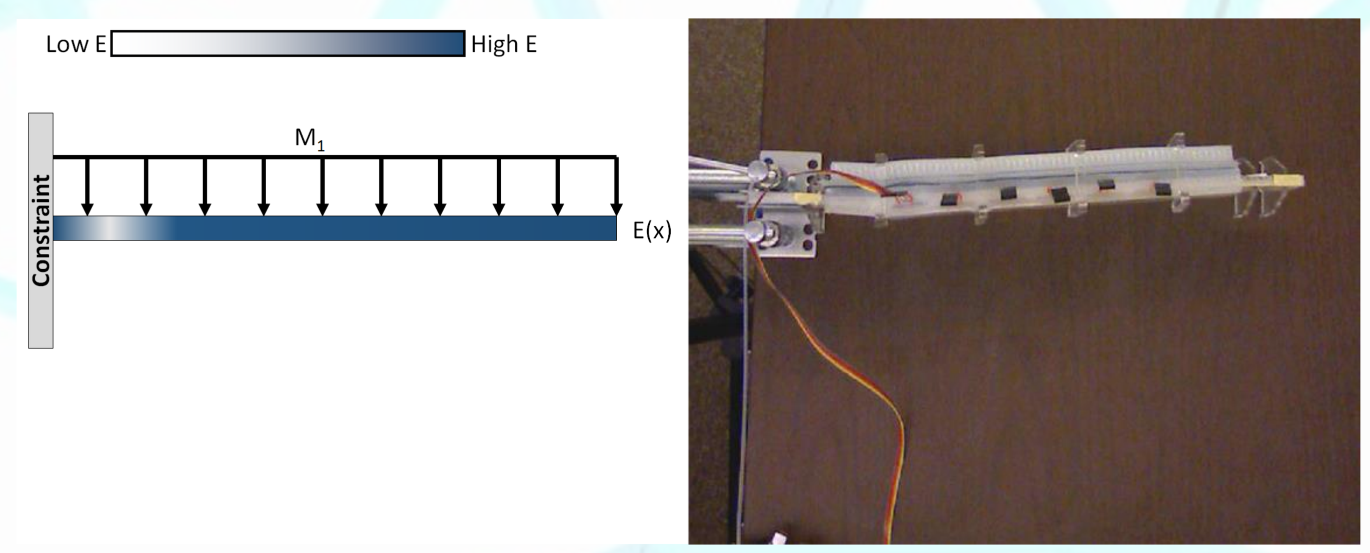

Figure: The embedded heaters are used to change the stiffness in the bar in a localized region while a simple 1D actuator is used to apply a load to the beam.

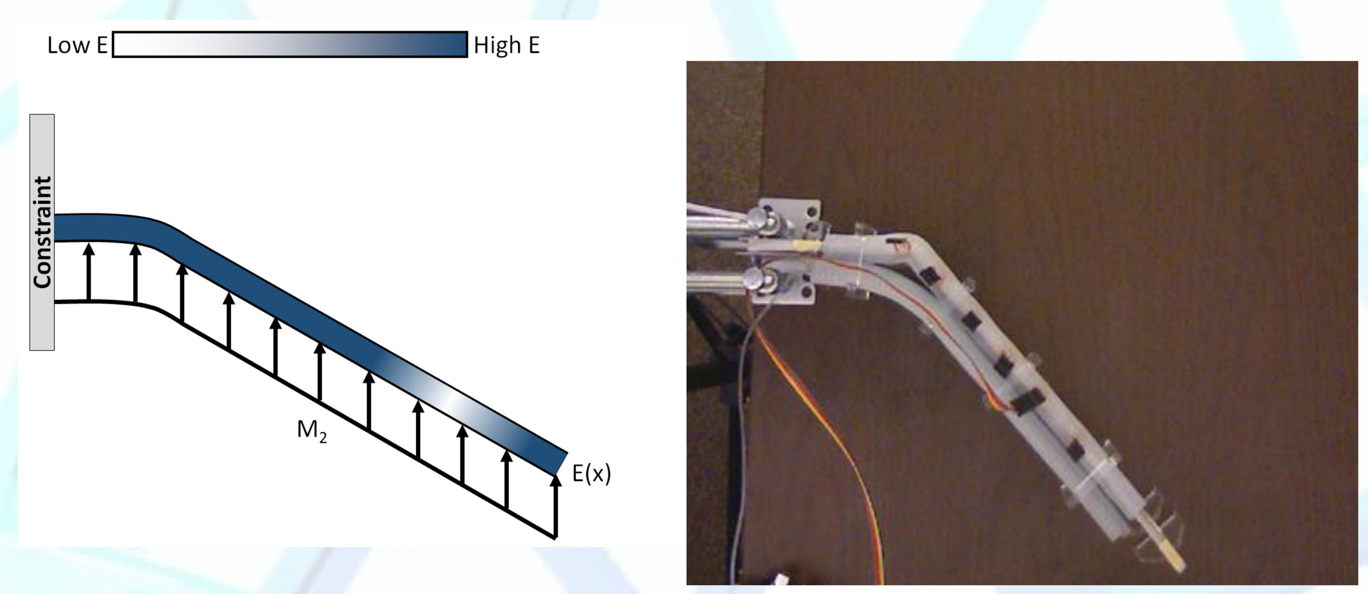

Figure: The process is repeated to induce curvatures in the opposite at different locations in the beam.

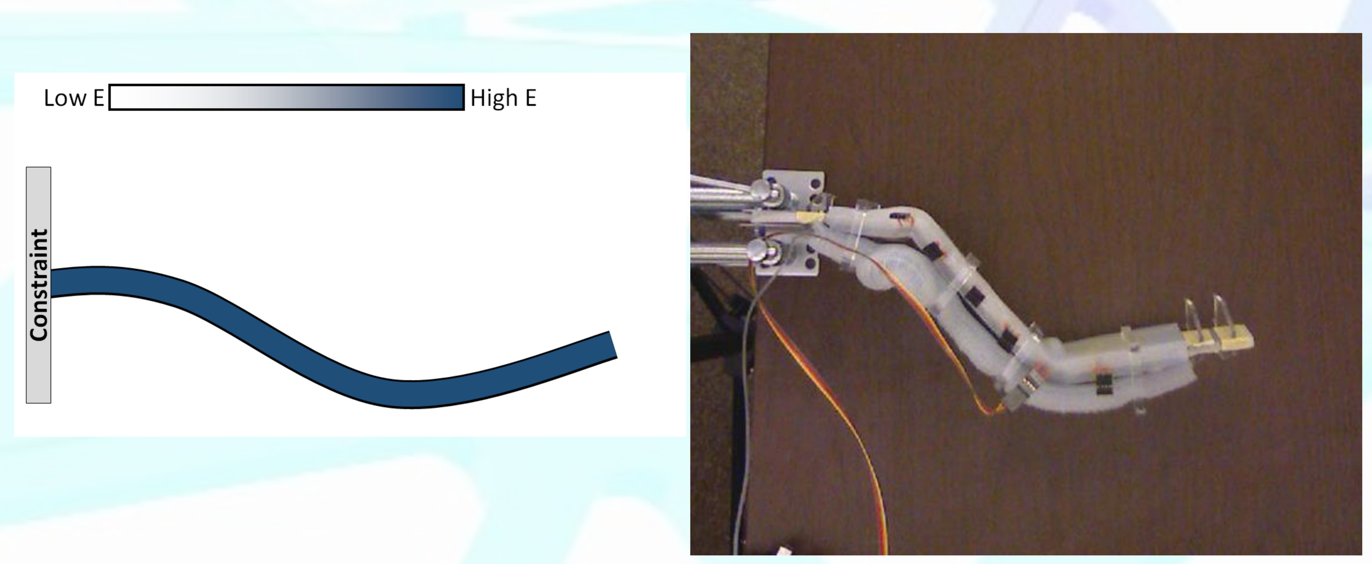

Figure: The resulting configuration. The beam returns to its normal stiffness and the shape is retained.

Potential Impact

Computational meta-materials are enabled by advances in polymer sciences, miniaturization of computing elements, and manufacturing capabilities, and have the potential to become ubiquitous in aerospace, civil engineering, robotics and everyday objects whose surfaces and structural elements will become multi-functional.

Figure: From left-to-right , CMMs with the ability to sense touched textures, sensorial enhancing clothing for the hearing impaired, amorphous façades for smart buildings.

By tightly integrating SAC^2 inside the material at high density and in large numbers, CMMs are the ultimate cyber-physical system, posing unprecedented challenges in distributed control and global-to-local programming that the CPS community has the ability to address.

Key Challenges

- Developing the distributed control laws needed to achieve arbitrary shape changes that encompass both the continuous material and the discrete computational elements.
- Power management issues that arise from embedding computation into a material.
- The interplay between the embedded information network, the embedded power network, and the distributed algorithms is tightly coupled.

Publications

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• S. Ma, H. Hosseinmardi, N. Farrow, R. Han, N. Correll: Establishing Multi-Cast Groups in Computational Robotic Materials. In: IEEE Int. Conf. on Cyber, Physical and Social Computing , Besancon, France, 2012.
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• A. McEvoy, N. Correll: "Shape Change Through Programmable Stiffness." In: Int. Symp. on Experimental Robots (ISER), 2014 (Under Review)

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